

1-D Imaging of O₂, N₂, CO₂, H₂O, and Jet-A Fuel using Vibrational-Raman and Mie Scattering of Tunable KrF laser Light from a High-Pressure, Turbine-Engine Combustor^{*}

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ABSTRACT

NASA Glenn Research Center has previously developed several unique test facilities that allow optical access to combustor elements that burn jet fuel and operate up to 60 bar. We describe here the application of UV-Raman for combustion diagnostics in one of these facilities. The use of tunable excimer diagnostics is well established. Here for the first time, we apply it to analyze the flow in a high pressure, high temperature, advanced-concept jet engine combustor. The main difficulties are caused by the burning of Jet-A fuel, which contains a large fraction of polyaromatic hydrocarbons. These absorb laser light, thereby weakening the laser beam and causing interfering LIF to be emitted. With some test conditions are a large number of fuel drops. These cause laser beam absorption and refraction, and also result in a huge Mie interference. Nevertheless the method was applied successfully. It could easily be greatly improved by the application of some straightforward changes..

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INTRODUCTION

In order to help the development of advanced turbojet aircraft power plants, we are designing and testing low emission combustor concepts. These combustors will likely operate at high temperatures and at pressures that are 3-5 \times higher than combustors in the current fleet. From a test and measurement viewpoint, these advanced combustors present some unique challenges (Locke, *et al.*, 1997; Locke, Hicks, *et al.*, 1998;). In general, there is an increasing need for non-intrusive measurements, more simultaneous multi-point measurements, and more quantitative measurements. NASA Glenn Research Center has developed several unique test facilities that allow optical access to combustor elements that burn jet fuel and operate up to 60 bar. These facilities, and previous measurements and results, are described elsewhere. In the previous work, we used laser-induced fluorescence (LIF) and Mie scattering. We combined multiple planar measurements of both LIF (PLIF) and Mie scattering (PMie) and obtained 3-D images. We quantified Mie scattering data by comparing them to Phase/Doppler Particle Analyzer measurements. PLIF measurements to date, however, have been qualitative.

The UV-Raman technique described here offers a complement to the PLIF and Mie methods. It also has the potential for calibration of our PLIF measurements by providing an independent measurement of species number density at known points within the PLIF images. We describe here the first test of tunable-excimer laser-based spontaneous-Raman measurements in a high-pressure advanced injector that burns Jet A fuel. We obtained 1-D images of O₂, N₂, CO₂, H₂O, and fuel.

Recently, 1-D (along the line of the laser beam) excimer-based Raman imaging of scattered light, collected through an imaging spectrograph, has received increasing attention (Reckers, *et al.*, 1993; Nandula, *et al.*, 1992; Rothe and Andresen, 1997; Knapp *et al.*, 1997; Gu, *et al.*, 1997). With 1-D Raman imaging, the variation of densities of a number of species along a line can be obtained simultaneously. That means that the ratios of intensities from the various species are independent of laser intensity variations, of window fouling, and of beam absorption by the medium. Because the Raman signal-strength in a gas is directly proportional to species density, the method is particularly attractive for use in high-pressure experiments, because signals are correspondingly larger. The linear Raman technique offers the additional potential for temperature measurement using the ideal gas law and the measured densities.

A tunable excimer laser was used in this work because it has a large light energy per pulse, it can be tuned away from interfering LIF transitions, and it has a short wavelength λ . The ratio of the Raman intensity to that of laser light increases approximately as $1/\lambda^4$.

In summary, the advantages of the Raman technique for this test include, (a) the high gas density, large laser energy, and short wavelength each serve to increase the Raman signal, (b) the signal from each species remains a linear function of its density, and c) the *relative* densities of all majority species are simultaneously acquired with good precision.

One of the challenges to a successful quantitative linear UV-Raman measurement in these experiments is the presence of polycyclic aromatic hydrocarbons (PAH) in the fuel. Jet A is widely used to fuel commercial aircraft. There are standard specifications (ASTM, 1998) for the fuel, but these are mainly for physical properties. It has many chemical constituents and its composition can vary considerably, depending on the source of the crude oil and the particular refinery operation. It mainly consists of hydrocarbons with nine to fourteen carbon atoms per molecule.

Most constituent hydrocarbons in Jet A fuel are saturated. Those are best for our method because they do not absorb at the KrF excimer laser's 248-nm output wavelength. Unfortunately, there is typically a 10-20% fraction of PAH, while 25% by volume is the maximum allowed (ASTM, 1998). These aromatics absorb both the incident laser light and the scattered Raman light, and thus their presence complicates the diagnostics. Some also re-emit light at longer wavelengths, and thus provide interfering LIF. Further, fuel droplets can refract and/or absorb the laser light, thereby producing variations in the laser intensity in the region to be investigated (Eisenberg, 1995). These problems variations do not affect measurement of the *ratios* of densities of species.

EXPERIMENTAL FACILITIES AND PROCEDURES

Facility

The NASA facility has been described previously (Locke, *et al.*, 1997; Locke, Anderson, *et al.*, 1998; Locke, Hicks, *et al.*, 1998). The combustor rig used in this study is a 76 mm \times 76 mm flame tube. It is equipped with UV-grade fused silica windows that are 51 mm high, 38 mm

long (in the flow direction) and 13 mm thick. These are cooled with a film of nitrogen that results in inner window temperatures that are less than 980K.

We use a lean, pre-mixed, pre-vaporized injector. It is proprietary and can not be described in detail, although a general schematic is shown elsewhere (Nguyen, *et al.*, 1999).

Our inlet air temperature ranged between 615K and 787K and the pressure between 4.5 and 17.7 bar. Fuel/air equivalence ratios were between 0.36 and 0.64. Air mass-flows were in the range 0.12 – 0.48 kg /s. According to the specifications for Jet A, the first 10% of the fuel is distilled at 478 K, and 100% is vaporized at 573 K. Within the short period between the time that liquid fuel is injected, and the time it reaches the observation region, it may not completely evaporate. Results, to be described later, indicate that at our lowest inlet temperature, 615K, there were still many fuel droplets in our observation region, while at 787K no droplets were observed.

For comparison, some measurements were made without any fuel injection (i.e., with air only). Here the temperature and pressure ranges were 296 to 730K, and 13.9 to 16.2 bar respectively.

Optics and Instrumentation

We used a modified Lambda Physik model EMG150-EST excimer laser. The major modification was the use of a "single-pass" configuration." (Grünefeld, et al., 1996). Experience with this arrangement has shown that the light is $\approx 90\%$ linearly polarized, is nearly 1 cm^{-1} in bandwidth, has an approximately 13-ns pulse length, and can be tuned from 247.8 nm to 248.8 nm. The pulse energies are typically 200 mJ. The laser is operated at a $\approx 3\text{ Hz}$ repetition rate because the beam's energy/pulse, and its locking efficiency, degrade at faster rates. The species OH, and vibrationally excited NO or O₂ have excitation lines that lie within the laser's tuning range. We successfully adjusted the laser wavelength to eliminate LIF from these molecules. Unfortunately LIF from PAH occurs at all laser wavelengths.

The optical beam transport system is described elsewhere (Locke, Hicks, *et al.*, 1998). The laser beam traveled $\approx 13\text{ m}$ to the test section and was steered there with a set of remotely controlled mirrors. Its size was maintained by passing through appropriate lenses. We used a spherical lens to reduce the beam's cross section to roughly $0.5 \times 1\text{ mm}$ in the test region. The

lens' focal length was chosen as a compromise between maximizing the homogeneity of the beam's cross section in the test region (long focal length) and minimizing the energy density at the fused silica windows (short focal length). Because we badly burned a window during the initial optical setup, we chose a short focal length.

The laser beam passed vertically through the combustor. It emerged through another window that served to reduce reflected light. The Raman light was measured in a direction that is perpendicular to the laser beam and, in order to maximize the signal, that is also perpendicular to the direction of its electric vector (Rothe and Andresen, 1998). It was gathered with a 38 mm diameter lens, located about 20 cm from viewed region (i.e., a solid angle of 0.03 sr), and a Raman image of the desired region was projected onto the slit of an imaging spectrometer. That instrument, in addition to dispersing light, achieves 1-D spatial resolution because it retains the spatial information that exists at its entry slit. We use a 250 mm, f/4, Chromex Model 250IS. In this experiment the optics were adjusted to view a 6-mm long region within the 51-mm height available from the window dimension.

We filtered the light going into the spectrometer by using a cuvette containing a dilute solution of butyl acetate (BuAc). Pure BuAc has been recommended (Hargis, 1981) for use with KrF light, because of its sharp cut-off between 250 nm and 254 nm. In a 10-mm path, pure BuAc attenuates 248-nm light to 10^{-4} , but transmits 60% of the O₂ Raman line at 258 nm. In this study, its concentration was adjusted so that the Rayleigh intensity, from air, was comparable to the Raman signal. We had hoped to obtain useful information from the Rayleigh intensities, but the effect of reflections, and of Mie scattering, made that impractical. In retrospect, the use of pure BuAc might have been better.

The light was transmitted by the spectrograph to a Princeton Instruments intensified CCD camera (Model ICCD-576G/RB) that was located on the spectrograph's exit plane. The camera's intensifier gate was set at 100 ns, which was short enough to suppress all cw light, but long enough to prevent jitter problems.

Our observed Raman vibrational lines are, in cm^{-1} , carbon dioxide 1388 and 1285, oxygen at 1556, nitrogen at 2331, fuel (mainly C-H stretch) at 3050, and water at 3657. The abscissas of our spectra are labeled wavelength, but are actually the CCD pixel number. The relevant pixel numbers are: the laser frequency (Mie, Rayleigh, and reflections) is ≈ 50 , carbon

dioxide ≈ 190 , oxygen ≈ 210 , nitrogen ≈ 315 , fuel ≈ 370 , and water ≈ 550 . The image wavelengths, while not labeled, have the same range of pixel numbers as the spectra. The scale is roughly linear in wavelength.

RESULTS AND DISCUSSION

The data described were *all acquired in a ten-hour period*. Because of the facility schedule, we could not repeat measurements and because of safety considerations, we could not physically access the combustor, filter, spectrometer, or camera during the actual test. As a result of this we were unable to fix the defective laser-power meter that was located near the combustor, and thus had no reliable pulse-energy values.

We measured at 31 different test conditions, eight of which were without fuel. Temperature and pressure values were acquired by standard test cell instrumentation.

For each of the eight non-fuel conditions, we acquired both 1-D images, and spectra. Each image and spectra is an average of 100 laser shots. The averages were summed on the CCD. Single shot images were also acquired.

For each of the 22 combustion conditions, we recorded and stored single-shot images, a series of 100 single shot spectra, 100-shot images, and 100-shot spectra.

Air-Only

The "air-only" results allow us to check the precision of some aspects of the measurements. Figure 1 is a 1-D image obtained from air by summing 100 laser shots. The wavelength is the abscissa and distance is the ordinate. Because the air is homogeneous, and does not absorb the laser light, the asymmetry along the ordinate is caused by optical misalignment. The three peaks, from left to right, are at the laser wavelength, and those of the vibrational Raman oxygen and nitrogen lines, respectively

Figure 2 shows two spectra from the same conditions as Figure 1. The spectrum labeled "100-shot air" could also have been obtained by summing the pixel columns in Figure 1, but in this instance was independently acquired. We also show a spectrum from a single laser-shot, which is noisier.

We can sum areas under such peaks and use these areas as a measure of Raman signal-intensity. We find that all the nitrogen-to-oxygen ratios of Raman signal-intensities from our eight 100-shot spectra fall within a $\pm 2.3\%$ range. As was discussed above, this good precision might be expected.

As discussed above, we also tried to make use of the Rayleigh signal-intensities (Reckers, *et al.*, 1997). Unfortunately, even from "air-only," the ratio of intensities of nitrogen-Raman to Rayleigh had much larger variations. These were presumably caused by dust particles and/or surface reflections that contribute light at same wavelength as the Rayleigh line. An example is seen in the difference between these ratios in Fig. 2. Accordingly, we do not present a Rayleigh analysis here. The problem becomes even greater when Mie scattering from fuel also occurs (see below).

Figure 3 shows that, as expected, the nitrogen Raman signal-intensity is roughly proportional to the air density. We calculated the air density using the ideal gas law, which under the experimental conditions, is a good description (Dymond and Smith, 1980). Temperatures and pressures were supplied by the facility. We attribute the deviations from straight-line behavior in Fig. 3 to laser energy variations, but, because of the defective power meter, we could not monitor these.

Although the Raman line shapes are somewhat affected by temperature, no effort was made here to correct the data for this effect.

With Fuel

Figure 4 is a 1-D image that illustrates several relevant phenomena. This is a sum from 100-shots. From left to right are the peaks for the laser frequency, the Raman oxygen, and the Raman nitrogen. The oxygen line runs together with two CO₂ lines. The nitrogen line, as in Fig. 1, is stronger toward the bottom, because of the optical misalignment. The stronger line that is immediately to the right of the nitrogen is fuel (mainly C-H stretch), and the other strong line, near the right edge, is water. Because the O₂ line is not cleanly separated from the two CO₂ lines, we pay no further attention to either of these species here. However the chemical balance relates the amount of CO₂ to that of H₂O. The initial O₂ can be related to the essentially unchanging N₂, but it would be desirable to separate these contributions.

The horizontal streaks are caused by intense fluorescence from polyaromatic hydrocarbon (PAH) components of fuel. These streaks can be seen in a few single-shot images, but they are usually absent. That indicates that in 100-shot images, like Fig. 4, each feature arises from the contribution of a single shot. Because there is no corresponding Mie scattering, they are not caused by drops, but may be local vapor clusters of newly evaporated drops. These streaks are more frequent in the upper half of the image, and we see more fuel, and product water there. There is also an increasing amount of non-localized emission toward the right, which arises from fluorescence from PAH.

Figure 5 shows a set of 16 single-shot spectra that were acquired under conditions similar to those of Fig. 4. They are the first 16 of a 100-shot series of spectra, acquired at intervals of about 0.3 s. While each is noisy, the general outlines are apparent, and show a variety of phenomena. Remember that these images were acquired at intervals of about 300 msec, with the system nominally at steady state. All have a peak corresponding to the laser frequency, but its height is variable. Some rise steeply thereafter, suggesting fuel-drop fluorescence. Some show strong fuel and water constituents, while others have almost none. It is obvious that very different conditions exist within the field of view at different times.

Figure 6 shows 100-shot sums for two sets of data that had the same conditions as Fig. 6. The results are nearly identical. They differ only in the method of acquisition, as described above. Although each is the result of 100 widely different single shot spectra like those in Fig. 5, the sums nevertheless converge to a consistent result.

The nitrogen peak height in Fig. 6 is only about 10 % of that in Figure 2 for pure air. The nitrogen density in the hot combustion products might be reduced by about a factor of four, and the remainder is probably due to absorption by aromatics.

In principle, the average PAH density might be found from the slope of the baseline in plots like Fig. 6. However this is an LIF process, and quantitative interpretation is difficult.

Figure 7 shows conditions of lower temperature for which there are many fuel drops and accordingly high Mie scattering. These conditions lead to considerable laser absorption and thus weaker Raman signal-intensities.

Fig. 8 shows spectra for five different conditions. The bottom two were at approximately the same temperature, but the upper one had a 70 % larger density, correspondingly more

absorption and thus smaller peaks. The bottom trace and the third trace are from similar pressures, but the temperature has decreased for the third. The lower temperature leaves more droplets and so more Mie scattering signal and less penetration of laser light. The fourth trace is similar to the second trace. The fifth trace is at the lowest temperature, and has an enormous Mie peak. The sixth trace is a blowup of the data in the fifth, and is presented again to show that even under these severe conditions, the nitrogen and fuel peaks are clearly defined. In contrast to the other data sets, there is fuel, but no water, suggesting that that ignition has not taken place yet.

Possible improvements

There are many available experimental methods to improve the measurements. Trivial points are to connect a laser power meter, and to improve the optical alignment of the spectrometer.

Better filtering of the light, e.g., by two interference mirrors (Eisenberg, 1995) or by a more concentrated BuAc filter, would remove most of the disturbing Mie light.

The use of polarization properties to remove fluorescence interference is well established (Knapp, 1996). This could be done here by (a) improving the degree of polarization of the laser, (b) splitting the Raman light into two parts, (c) passing each through an appropriate polarizer, and (d) then subtracting the two signals.

A modern commercial tunable-excimer has about $16\times$ the repetition rate that we used. That means that the S/N ratio of all the data acquired here might be improved by about $4\times$.

Better detection optics would gather more light. For example, LaVision (Göttingen Germany) sells a Maksutov-Newton telescope with $f = 100$ mm and $f/1.4$. Kampmann, et al., have compared (Kampmann, 1995) the capabilities of the widely used Nikon achromat (which has a 105 mm focal length with $f/4.5$ and transmits from 220 nm to 900 nm) and a Maksutov-Newton telescope. They reported that the statistical uncertainty was about $3\times$ less with the telescope.

CONCLUSIONS

We have demonstrated that UV-Raman imaging can be used to diagnose an advanced jet injector at high temperature and pressure even when operated with Jet-A fuel. The combination of this diagnostic method, with the use of advanced test facilities, is a major step in establishing methods of devising active control of jet engines. Even in this single-day's run we have been able to accumulate a mass of data from varying facility conditions.

Our signal to noise ratio is adequate to obtain single-shot spectra, and these have shown that even in this steady flow combustor, conditions change drastically with time, as might be expected for turbulent reactive flow. Nevertheless reliable averaged data is obtained. Whether averaged data or the instantaneous values are most useful is not clear

The Raman method is particularly good for ratios of densities of various species. We again must ask whether the relatively precise averaged values are significant. As an extreme example, if the fuel/air equivalence ratio were zero on nine shots, and thus can not ignite, and is ten on the next shot, and can't ignite either, what good is it that the average is one.

The method can be improved considerably over that obtained for these measurements.

REFERENCES

- ASTM D 1655-98 (1998) Standard specifications for aviation turbine fuels, (American Society for Testing and Materials, West Conshohocken, PA, 1998).
- Dymond, J. H. and Smith, E. B. (1980) *The Virial Coefficients of Pure Gases and Mixtures, a Critical Compilation*, Clarendon Press, Oxford, .
- Eisenberg, S. (1995) Raman Spektroskopie an einer Zerstäuberflamme, Max Planck Institut für Strömungsforschung, Göttingen, Germany, Bericht 104/1995.
- Gu, Y. W., Rothe, E. W. and Reck, G. P. (1997) Imaging of H₂ Densities via Rotational Raman Scattering of KrF Laser Light, *J. Raman Spectrosc.*, **28**, 605.
- Hargis, P. J., (1981) Trace Detection of N₂ by KrF-laser Excited Spontaneous Raman Spectroscopy, *Appl. Optics*, **20**, 149.
- Grünefeld, G., Andresen, P., Schlüter, H. and Rothe, E. W. (1996) Operation of a Tunable Excimer Laser with KrF and ArF without Cassegrain optics, *Appl. Phys.*, **B62**, 241.
- Kampmann, S., Seeger, T. and Leipertz, A. (1995) Simultaneous Coherent anti-Stokes Raman Scattering and Two-dimensional Laser Rayleigh Thermometry in a Contained Technical Swirl Combustor, *Appl. Optics*, **34**, 2780.
- Knapp, M. (1996) *UV laser spectroscopy applied to in-cylinder phenomena of spark-ignition engines* Cuvillier Verlag, Göttingen, Germany.
- Knapp, M., Beushausen, V., Hentschel, W., Manz, P., Grünefeld, G., and Andresen, P. (1997) In-cylinder Mixture Formation Analysis with Spontaneous Raman Scattering applied to a Mass-production SI Engine, SAE paper No. 970827, Society of Automotive Engineers, Warrendale, PA.
- Locke, R. J., Hicks, Y. R., Anderson, R. C., Zaller, M. M. and Schock, H. (1997) Imaging Fluorescent Combustion Species in Gas Turbine Flame Tubes: On complexities in Real Systems, AIAA paper No. 97-2837, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, San Diego, CA.
- Locke, R. J., Anderson, R. C., Zaller, M. M. and Hicks, Y. R. (1998) Challenges to Laser-based Imaging Techniques in Gas Turbine Combustors For Aerospace Applications, *NASA Technical Memorandum*, NASA-TM-208649.
- Locke, R. J., Hicks, Y. R., Anderson, R. C. and Zaller, M. M. (1998) Optical Fuel Injector Patternation Measurements in Advanced Liquid-fueled High Pressure, Gas Turbine Combustors, *Combust. Sci. and Tech.*, **138**, 297.
- Nandula, S. P., Brown, T. M., Cole, W. A., and Pitz, R. W. (1992) Simultaneous Multi-species Multi-point Measurements in H₂-air Flames using a Narrow-band KrF Excimer Laser, in AIAA paper No. 92-3348, AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference, Nashville, TN.
- Nguyen, Q.-V., Mongia, R. K. and R. W. Dibble, (1999) Real-time Optical Fuel-to-Air ratio Sensor for Gas Turbine Combustors, *NASA Technical Memorandum*, NASA-TM-1999-20941.

Reckers, W., Hüwel, L., Grünefeld, G. and Andresen, P. (1993) Spatially Resolved Multispecies and Temperature Analyses in Hydrogen Flames, *Appl. Optics.*, **32**, 907.

Reckers, W. Gu, Y. W. Rothe, E. W. and Voges, H. (1997) Rayleigh Scattering of Excimer Laser Light from some Simple Molecules at 193 nm and 248 nm: the Effect of Polarization upon Imaging Diagnostics,” *J. Appl. Spectrosc.*, **51**, 1012.

Rothe, E. W. and Andresen, P. (1997) A Review of the Application of Tunable Excimer Lasers to Combustion Diagnostics, *Appl. Optics*, **36**, 3971.

FIGURE CAPTIONS

Figure 1. 1-D image of air at 550K and 15 bar. The image is from the sum of 100 laser shots. The three peaks, from left to right, are the laser wavelength (Rayleigh scattering plus reflections), and the Raman light from oxygen and nitrogen. The abscissa is wavelength. The ordinate is distance within the combustor: about 6mm are viewed.

Figure 2. Raman spectrum obtained with air 550K and 15 bar. The top spectrum is from a single shot; the lower is the sum of 100 shots. The bottom spectrum is equivalent to a sum of the 1-D image intensities (summed vertically) like those in Fig. 1.

Figure 3. Plot of Raman nitrogen signal as a function of the density of air. Each point is the sum of 100 shots. All of our air-only conditions are included. The deviations from linearity are probably caused by variations in laser energy.

Figure 4. 1-D image of combustor at starting with air at 755K and 10.7 bar. The image is from the sum of 100 laser shots. The first three peaks, from left to right, are at the laser wavelength (Rayleigh scattering plus reflections), and the Raman light from oxygen and nitrogen, as in Fig. 1, although some carbon dioxide overlaps the oxygen. The next two are from fuel (C-H stretch) and water. The abscissa is wavelength. The ordinate is distance within the combustor.

Figure 5. Single shot spectra of combustor at 756K and 10.2 bar. These are the first 16 spectra of a 100-point run. They differ greatly among each other: this is also observed under other conditions. The ordinate scale is the same for each, but the intercepts have been arbitrarily displaced for ease of viewing. Four traces have horizontal straight lines at larger wavelengths. The straight lines indicate saturation of the CCD.

Figure 6. Two 100-shot spectra acquired under the conditions of Fig. 5. The laser frequency is near 50, and carbon dioxide \approx 190, oxygen \approx 210, nitrogen \approx 315, fuel \approx 370, and water \approx 550

pixels. The top was summed on the CCD and that at the bottom was the sum of 100 individual spectra. The latter include the sixteen shown in Fig. 5. Note that, in spite of the great diversity among the single-shot spectra, the sums are remarkably constant.

Figure 7. 1-D image of combustor at 615K and 10.7 bar. The Mie scattering from droplets completely dominates the scattered light, and the air constituents can barely be seen.

Figure 8. Five spectra obtained under different conditions, one spectrum is shown twice. The laser frequency is near 50, and carbon dioxide ≈ 190 , oxygen ≈ 210 , nitrogen ≈ 315 , fuel ≈ 370 , and water ≈ 550 . The spectra are vertically displaced from each other to make the plot less congested. Starting from the bottom trace, the conditions of temperature (K) and pressure (bar) of the air are (a) 757, 10.6; (b) 758, 17.4; (c) 702; 10.3, (d) 782, 10.2, and (e) 615, 10.7. The top trace is from the same data as from that below it, but has been multiplied by 5.
















